Tropical Cyclone Intensity and Structure: Improved Understanding and Prediction. Evaluation of Existing and Development of New Techniques for Global and Mesoscale NWP Model Assessment.

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LONG-TERM GOALS

I am now in the second year of this grant. My first goal is to finish work on finding reliable estimates of the theoretical limits to tropical cyclone (TC) forecast error for both track and intensity predictions. The emphasis now is on distinguishing between overall track errors, and position and timing errors at landfall. My second goal is to use both similar and new techniques to estimating the predictability limits of tropical cyclone *intensity* and *intensity change* out to at least 96 hours. Given that there remain large errors in TC prediction, my third goal is to *identify, quantify and reduce* these sources of errors. My fourth goal is to *improve the initial state* specification for TCs by continuing the development and application of 4D data assimilation procedures, particularly with respect to the ingestion of newly emerging data sources, including radar. Model development will continue through period of the grant as it is vital for improved predictions. I note here that for the third and fourth goals, special emphasis again will be placed on landfalling tropical cyclones, as they are the most destructive storms. My fifth goal is to address the crucial question of how best to evaluate the skill of NWP model. My sixth, and final, goal is the development of new statistical and statistical-dynamical procedures for TC forecasting. The above goals all have implications for transitions.

OBJECTIVES

I now have six main scientific objectives now, instead of the original five. My first two scientific objectives remain unchanged. They are: to complete work on estimating the intrinsic limits of predictability of tropical cyclone (TC) behavior, in particular mean forecast position errors and intensity errors. As already stated above, intrinsic limits of predictability for TCs exist because the equations governing the behavior of atmospheric systems, including TCs, are deterministically chaotic. Errors in initial conditions, model formulation and boundary conditions produce error growth that eventually renders the forecasts useless. The first two objectives are linked directly to the third, which is to carry out research directed at identifying and understanding the sources of errors in both the initial conditions and the model formulation, and to reducing these errors. This objective is the major part of the program of numerical analysis and prediction in this proposal. My focus will be largely on TCs that are approaching or making landfall, as they are the most devastating in terms of loss of life and property. The fourth objective is the continued development of my 4D-VAR data assimilation scheme. The sub-components of the third objective are to improve upon the 4D-VAR scheme, especially its

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efficiency, and its ability to ingest the many emerging data sources such as the satellite and radar data. My fifth objective is to evaluate existing schemes for assessing NWP model performance, and to develop alternative procedures. Present methods of assessment are not acceptable as they frequently are biased towards the NWP models or are too scale independent, unduly rewarding smooth forecasts and penalizing detailed predictions. In particular, new assessment schemes are required for TC model forecasts, as they are not well handled by conventional measures of skill, given the many scales and the range of variables that need to be assessed. As ensemble techniques begin to dominate forecasting systems, the need for new assessment procedures has increased. Finally, a sixth objective has been added during the FY03 period. I have returned to earlier work on the development and testing of statistical techniques for either stand-alone forecasting or to correct TC model predictions.

APPROACH

My approach for the six goals is as follows. The methodology employed for the first goal was explained fully already in the ONR FY01 and FY02 reports and in the literature. Two distinct techniques yielded almost identical answers. One approach was to generate an ensemble of initial model states using the archived data sets from various operational global NWP centers around the world The initial fields produce corresponding ensembles of forecasts at 12 hourly intervals out to 72 hours, after re-setting the TC positions back to their best track locations every 12 hours. The second technique was based purely on observational data. A non-linear systems approach is applied to the archived best track data sets. In this case, the spread of initially close pieces of TC trajectories is calculated over a 72 hour period for all available data sets. My second goal has been to apply the procedures that proved to be successful in achieving the first goal to the very difficult problem of estimating the predictability characteristics of TC intensity and intensity change. The task was a very large one with the goal again being to calculate predictability limits and how close we are to those in practice. These limits have now been compared for the various TC basins and provided information about how close current operational models are to the limits of predictability. The third goal has been to obtain model simulations with much more realistic TC structure, intensity, intensity change and motion as TCs approach landfall. The third goal links directly with my fourth goal, which is to employ my research program of data assimilation and NWP model prediction to obtain more realistic TC structure and intensity than has been achieved hitherto. Before this work began, I had been producing steadily improving forecasts of TC tracks but had failed to capture the intensity and intensity changes of the TCs. This failure is of extreme importance for TCs at or nearing landfall. The procedure adopted was to use and adjoint sensitivity approach to identify the contributing factors to intensity change and the improvement in the forecasts themselves. In FY03 I have continued to use four dimensional variational assimilation procedures without TC bogussing, taking advantage of high spatial-temporal frequency satellite derived data of various types and as many other sources of data as possible, especially radar data. The approach to the fifth goal has been to compare existing measures of assessment of NWP model skill with alternative measures. Initially, the alternative measures have been simple, but have clearly illustrated a need to augment, or even replace in some case, existing measures. The approach to the sixth goal has been to use the Atlantic basin TC data base to generate conditional probabilities for predicting the future tracks and intensities of Hurricanes in that basin. An example is given in the Results section below.

WORK COMPLETED

This grant is now near the end of its second year and is maturing well with work proceeding towards all six objectives. My work on the first goal is now completed and has either been published or been

submitted for publication (Leslie and LeMarshall, 2002, LeMarshall and Leslie, 2003). The recent work has focussed largely on reducing mean track errors for TCs that are regarded as difficult to predict. I have also extended the work to new basins, including the Bay of Bengal and the south China Sea, in collaboration with the researchers from Indian Meteorological Service, the Chinese Meteorological Agency and the Japan Meteorological Agency. The results are currently submitted and await reviewers' comments. My second goal of applying the same procedure to TC intensity predictability has also proceeded, with the emphasis again being on the more difficult storms. This work has produced some intriguing and unexpected results, most notably the large variations from basin to basin. Further development of the HIRES data assimilation and prediction system has proceeded, with the incorporation of new data from radar and satellite sources. This work also has been accepted for publication (Leslie et al. 2002 and LeMarshall and Leslie, 2002). My fourth goal of understanding the factors contributing to improving the forecasts of TC intensity and intensity change, especially for landfalling TCs, has yielded results. The primary research tool used in this work has been the continued application of an adjoint sensitivity approach. The procedure enables the impact of selected variables in the initial state to be quantified. The adjoint sensitivity work recently carried out by the PI has revealed precursors of TC frequency, motion and intensity. These precursors are at very different time scales, ranging from seasonal down to days and even hours. One paper has been published (Leslie et al., 2002). Thus far, the work has exhibited predictive and understanding capacity for the 1997/98 and 1998/99 seasons in the eastern Indian Ocean basin. Extension to the Pacific and Atlantic TC basins has continued in FY03, with two graduate students at the University of Oklahoma working in these areas as the basis of their thesis research. One student is in the final stages of thesis preparation. The question of the relative importance of initial /boundary errors and model formulation errors also has arisen during the PI's work in FY03 and has been addressed in joint work with the City University of Hong Kong. A paper has been written and is in press (Zhou et al., 2003). This area of research will continue to be pursued as it has implications for predictability, ensemble techniques and other procedures that are based on the assumption that the NWP model either are small compared with initial analysis errors or are not known well enough to be incorporated directly.

RESULTS

I now describe the main results for FY03. The results are now complete for the first goal, which was to determine how close current NWP models are to our best estimates of the limits of predictability for mean absolute TC track errors. The chaotic nature of the systems and the governing equations results from the non-linearity of the system together with the many feedback processes that take place in such complex systems. The major finding of FY01 and FY02 was the potential for TC track errors to at least be *halved.* This finding has been confirmed by work in FY03. A second set of results concerns the performance of the NWP systems presently at the core of my ONR research program. This model is the High Resolution (HIRES) data assimilation and prediction system. Largely using ONR support, this system has been developed over six years, for use in TC applications by the PI, various graduate students and part-time time research associates. It has continued to undergo development in FY03, especially in the area of data assimilation and representation of cloud microphysics.

TC Motion – enhancements in the data base, the 4D data assimilation procedure, the initialization scheme and the model itself. The data base enhancements have come from satellite-derived wind vectors from geostationary satellite cloud and water vapor imagery; from scatterometer winds, Topex-Poseiden analyses of water surface elevation anomalies; radar data; AWS networks; special observing periods and the imminent launching of a new generation of sounders with thousands of channels.

TC Structure – two approaches continue to be used in FY03. First, the major structural features of TCs must be identified and understood, from both observations and numerical simulations. Second, the HIRES system is being run at resolutions of 5 km or less to provide simulations that are as realistic as possible to enable the fine structure of the TC to be simulated. . Figure 1 shows the impact of radar data for tropical storm Allison which made landfall near Houston in June 2001.

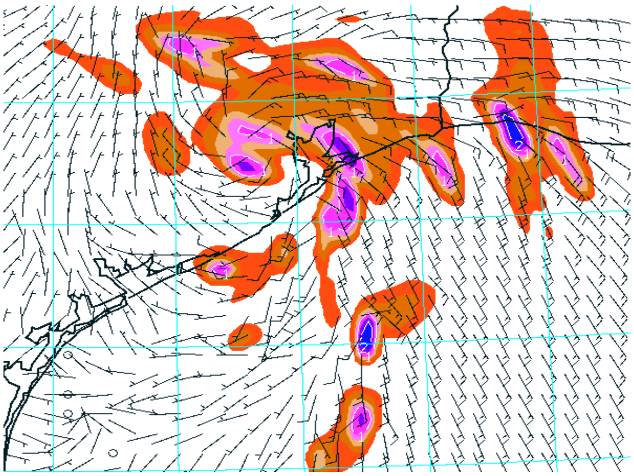

Fig. 1 (a) The 24 hour forecast wind field at the first σ level (σ = 0.999) and the forecast rainfall rates at 00UTC 6 June 2001 for

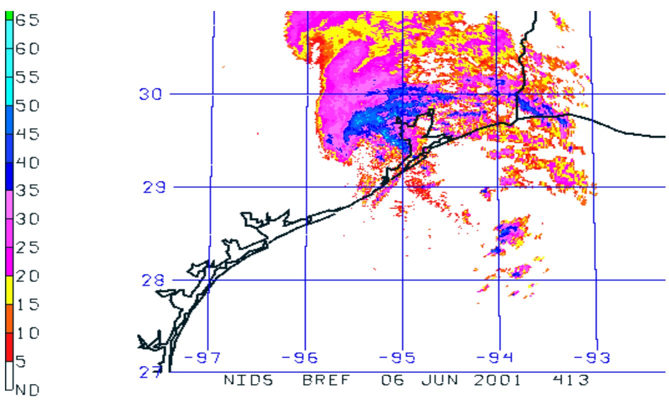

Fig. 1 (b) The wind field at the first σ level (σ = 0.999) and the rainfall rates at 00UTC 6 June 2001 for Tropical Storm Allison using the 4D VAR assimilation

IMPACT/APPLICATIONS

I have confirmed earlier work which showed that TC track forecast errors remain that present track errors are still at least twice that which can be achieved. Such a large gap between practice and theoretical limits implies further possibility for large error reductions. A second impact in FY03 is from the use of careful quality controlled, high resolution, data from existing and new sources; developments in continuous (4D) assimilation; and ongoing model improvements. Third, I confirmed FY02 findings that realistic intensity forecasts are enhanced by high model resolutions of 5km or below. TC simulations that have many of the observed features of actual TCs will soon be routine. Fourth, the adjoint sensitivity techniques developed earlier continue to improve our ability to predict TC motion, structure, intensity, and intensity change. Fifth, existing methods for assessing NWP model performance are too simplistic and favor the NWP model systems. New techniques are now being tested. Sixth, the precursors of TC activity and intensity identified in FY 02 in the eastern Indian Ocean, northwest of Australia have been extended to the western Indian Ocean. These precursors exist at the inter-seasonal level down through the intra-seasonal level, to time-scales of days and even during

the life cycles of TCs. Seventh, the statistical approach being developed had its first real-time test with Hurricane Isabel, and the predictions appear to have been skilful. Early results for the Atlantic basin were presented at the February 2003 AMS Annual Meeting and showed a significant decrease in model skill, especially for the North and South Carolina and Virginia coasts. An example from the 2003 season is given for Hurricane Isabel (see Figure 2).

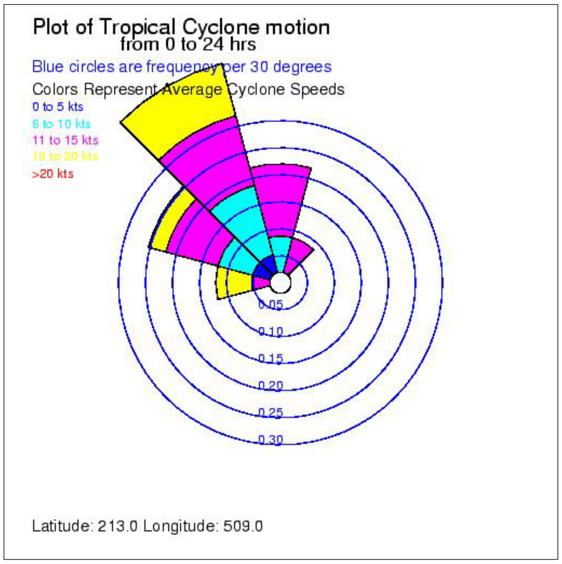

Fig. 2 A 24 hour probability distribution of the predicted direction and speed of motion for Hurricane Isabel, just before it began to move to the northwest, towards the US east coast. At the time, Isabel was at lat 21.3N; long 50.9W. This statistical model did as well as the NWP models, but at this stage of development the predictions are only for 24 hours ahead. Forecasts will be extended in FY04 to 48 hours.

RELATED PROJECTS

I am a co-PI on the CBLAST grant entitled “The Impact of Air-Sea Interaction Research on Larger-Scale Geophysical Flows.” with Dr Michael Banner of The University of New South Wales. I also continue to interact with Dr Wang Yuqing, University of Hawaii, on cloud microphysics schemes.

SUMMARY

The work being carried out in this proposal is aimed at increasing our knowledge base of tropical cyclones in a number of areas. Tropical cyclones, which are also referred to as hurricanes and typhoons, are the most devastating storms on earth. As such it is vital to understand and to predict their behavior. To do so in an accurate and timely manner requires research on their motion, their structure, their intensity, especially when nearing land. To achieve these aims, a program of data collection and computer model simulations is being carried out, with the predictions being compared with observations of selected storms. Deficiencies in the initial data, the model formulation and the model predictions are then identified and research is carried out on improving these aspects. The ultimate goal, expressed as succinctly as possible, is the provision of accurate, timely and reliable model predictions of TC tracks and intensity, especially for storms that threaten coastlines. The ONR funded research program I am carrying will help make the School of Meteorology, University of Oklahoma, an international focal point in tropical cyclone research.

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HONORS/AWARDS/PRIZES

I have been received one award and one honor in FY03. The award is the Australian Meteorological and Oceanographic Society Medal for 2002. The honor is an (accepted) invitation to become a member of the International Advisory Committee of the Shanghai Typhoon Institute.